

# Structure and production of $\Theta^+$

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We study properties of the pentaquark particle  $\Theta^+$  with emphasis on the role of chiral symmetry. It is shown that when chiral force is sufficiently strong, the positive parity  $\Theta^+$  may be realized with a lower mass relative to the negative parity state. The decay width is then studied in the non-relativistic quark model. It is shown that the narrow width may be realized for the positive parity state, while the seemingly lowest negative parity state couples strongly to the continuum state resulting in a very broad width. Finally,  $\Theta^+$  production is studied in photo-induced and proton-induced processes. The polarized proton reaction provides a model independent method to determine the parity of  $\Theta^+$ .

PACS numbers: 12.39.Fe, 14.20.Gk, 13.40.Em

Keywords: pentaquark, parity, decay width

## I. INTRODUCTION

The observation of evidence of the pentaquark particle  $\Theta^+$  has triggered enormous amount of works both in experiments and theories [1]. The investigation requires new insight to understand the properties of the multi-quark system with at least five quarks [2]. It is a great challenge to explore from the conventional hadronic matter to a new type of matter eventually toward the quark matter. It is also expected that the study of the multi-quark system will provide information for non-perturbative QCD at low energies, which we have not yet understood well. The mechanism for the light mass and narrow width of  $\Theta^+$  is obviously an important issue to be solved together with the determination of its spin and parity. In particular, the parity reflects the internal motion of the state and should be a crucial observable for the development of the new field as described above.

In the previous studies of hadrons, the constituent quark model and the mesonic soliton model have been often used as typical QCD oriented models [3, 4]. The basic assumptions of these models look rather different, but various properties of hadrons, especially of baryons, have been reproduced in a similar manner once several fundamental parameters in the models are fixed appropriately. This is because many properties of the ground state hadrons are dictated mostly by the symmetry, especially the flavor symmetry of QCD. If we go to higher energy states, however, one expects to observe dynamical effects of the interaction, which should reflect the difference in various models. Therefore, it is of great importance to explore the properties of multi-quark systems in various models.

In this report, first we discuss the role of chiral symmetry on the parity and mass of the pentaquark particle. Chiral symmetry is the fundamental symmetry of QCD and its spontaneous breaking governs the dynamics of low energy hadrons. As we will see, the study of multi-quark systems reveals another interesting features of the dynamics of chiral symmetry. In fact, the success of the original work in the chiral soliton model has already implied its crucial role [5]. To see this point explicitly, we

adopt the chiral bag model which accommodates quark single particle levels depending on the strength of the pion-quark interaction at the bag surface [6]. The pion quark interaction induces level crossing between the positive and negative parity states, giving an intuitive way to understand the origin of the parity of  $\Theta^+$  [7]. The result of the chiral soliton model of positive parity  $\Theta^+$  and that of the naive quark model of negative parity may be explained depending on the strength of the pion-quark interaction.

As a physical quantity which reflects the parity, we investigate the strong decay of  $\Theta^+$ . For actual computation, we adopt the quark model and consider effects of different configurations of quark single particle wave functions of the spin, flavor, color and orbital spaces. The direct role of chiral symmetry for the decay amplitude itself should be studied separately, which we do not consider here.

In the second part we discuss production reactions of  $\Theta^+$ . Photo-induced and polarized proton induced reactions are investigated, where the total and angular distributions of the cross sections are studied. In particular, the latter provides a selection rule to determine the parity in a model independent manner.

## II. ROLE OF CHIRAL SYMMETRY FOR $\Theta^+$

Let us start with the quark model, which has been successfully applied to the description of conventional hadrons and should be tested also for the pentaquark state [8]. In a naive constituent quark model, valence quarks occupy single particle states which are given by the harmonic oscillator. Due to the degeneracy of the spin-flavor and color degrees of freedom, for the ground state of the pentaquark  $\Theta^+$ , four quarks of  $uudd$  and one antiquark  $\bar{s}$  occupy the lowest  $0s$  state, hence the configuration of  $(0s)^5$ . In the constituent quark model, the mass of the ground state is given by the sum of the five constituent quark masses. This amounts to be about 1.7 GeV when  $m_{u,d} \sim 310$  MeV and  $m_s \sim 500$  MeV are employed. The value 1.7 GeV is slightly larger than the

experimental value  $\sim 1.5$  GeV. The mechanism has been proposed to reduce the mass by the spin-flavor or spin-color interaction as mediated by the Nambu-Goldstone meson exchange or gluon exchange [2].

The parity of the  $(0s)^5$  configuration is negative, because the parity of  $\bar{s}$  is negative. Therefore, one would expect that the naive quark model would predict the negative parity state for the lowest pentaquarks. As will be shown later, however, such a  $(0s)^5$  configuration couples strongly to the  $KN$  continuum, resulting in a very wide decay width. In contrast, for positive parity state the decay width can be of order of 10 MeV.

If we make a positive parity pentaquark state in the quark model, one of the quarks must be excited into a p-wave ( $l = 1$ ) orbit. This costs another 500 MeV for the mass of  $\Theta^+$ . A relevant question is if there is a mechanism to lower such a high lying state as compared with the negative parity state. As shown in Ref. [9] the flavor dependent force due to the Nambu-Goldstone boson exchanges between quarks has a large negative matrix element for the most attractive channel of the pentaquark state.

In the chiral bag model, the change in the parity can be also illustrated by plotting quark single particle states as functions of the chiral angle at the bag surface (see Fig. 1) [7]. In the hedgehog configuration, the chiral invariant pion-quark interaction reduces to a spin-isospin interaction of the type  $\vec{\sigma} \cdot \vec{\tau}$  which resolves the degeneracy in the  $K^P = (j \pm 1/2)^P$  states, with  $K = j - 1/2$  state lowered and with  $K = j + 1/2$  state pushed up. Here  $K$  is the sum of the spin and isospin  $K = J + I$  [6]. As a consequence, for sufficiently strong pion-quark interaction, the  $K^P = 1^-$  level becomes lower than the  $K^P = 0^+$  level, where the  $(0s)^4(0p)^1$  configuration is realized, replacing the  $(0s)^5$  configuration as the lowest energy state. Hence the positive parity state could be the lowest energy configuration. In the chiral bag model for the nucleon, the bag radius of about  $R \sim 0.6$  (chiral angle  $F \sim \pi/2$ ) is favored [6]. If this would also be the case for the pentaquark, the mass of the positive parity state is slightly lower than the negative parity one  $\sim 1.7$  GeV.

### III. DECAY WIDTH

The decay of the pentaquark state going into one baryon and one meson is described by the fall-apart process as shown in Fig. 2 (left). The matrix element of such a process is written as a product of the so-called spectroscopic factor and an interaction matrix element,

$$\mathcal{M}_{\Theta^+ \rightarrow KN} = S_{KN \text{ in } \Theta^+} \cdot h_{int}. \quad (1)$$

The former  $S_{KN \text{ in } \Theta^+}$  is an amplitude to find in the pentaquark state three-quark and quark-antiquark clusters having the quantum numbers of the nucleon and kaon,

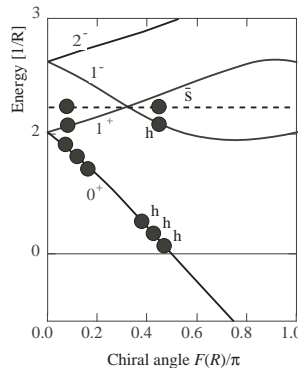


FIG. 1: Quark energy levels of the chiral bag model in the hedgehog configuration as functions of the chiral angle  $F$ .

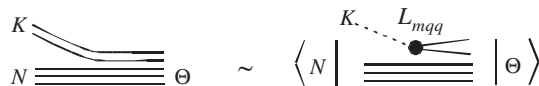


FIG. 2: Decay of the pentaquark state.

respectively. Explicit calculation for this factor was done in Ref. [10]. In the quark model, the interaction matrix element may be computed by the meson-quark interaction of Yukawa type:

$$L_{mqq} = g\bar{q}\gamma_5\lambda_a\phi^aq, \quad (2)$$

where  $\lambda_a$  are SU(3) flavor matrices and  $\phi^a$  are the octet meson fields. The coupling constant  $g$  may be determined from the pion-nucleon coupling constant  $g_{\pi NN} = 5g$ . Therefore, using  $g_{\pi NN} \sim 13$ , we find  $g \sim 2.6$ .

The transition  $\Theta^+ \rightarrow KN$  contains a matrix element of quark-antiquark annihilation of, for instance,  $\langle 0|L_{mqq}|u\bar{s}\rangle$  as shown in Fig. 2 (right). Details of calculation will be reported elsewhere [11], and here several results are summarized as follows. For the negative parity state of  $(0s)^5$ , the decay width turns out to be of order of several hundreds MeV, typically  $0.5 \sim 1$  GeV. In the calculation it has been assumed that the spatial wave function for the initial and final state hadrons are described by the common harmonic oscillator states. Also the masses of the particles are taken as experimental values, e.g.,  $M_{\Theta^+} = 1540$  MeV. For the result of the negative parity state of  $(0s)^5$ , the unique prediction can be made, since there is only one quark model states. The very broad width suggests that the  $(0s)^5$  state couples very strongly to the  $KN$  continuum and is hardly identified with a resonant state with a narrow width.

The computation for the positive parity state is slightly complicated, since the orbital excitation introduces additional degree of freedom when writing the quark model wave function. In fact, four independent configurations are available for spin-parity  $J^P = 1/2^+$  [8]. Here we consider three configurations which minimize (1) a spin-flavor interaction of one meson exchange [10], (2) a spin-color interaction of one gluon exchange, and (3) the

$S = I = 0$  diquark correlated state as proposed by Jaffe and Wilczek [12]. The resulting decay widths are about 80 MeV, 40 MeV and 10 MeV, respectively. The diquark correlation of (3) develops a spin-flavor-color wave function having small overlap with the decaying channel of the nucleon and kaon. The decay width may be further suppressed by including correlations of spatial wave functions. Therefore, in the quark model, it is possible to reproduce the experimentally observed narrow width of  $\Theta^+$  for the positive parity.

The small values of the decay width for  $J^P = 1/2^+$  as compared with the large values for  $J^P = 1/2^-$  may be explained by the difference in the coupling structure; one is the pseudoscalar type of  $\vec{\sigma} \cdot \vec{q}$  and the other the scalar type of 1. The former of the p-wave coupling includes a factor  $q/(2M)$  which suppresses the decay width significantly as compared with the latter at the present kinematics,  $q \sim 250$  MeV and  $M \sim 1$  GeV, when the same coupling constant  $g_{NK\Theta}$  is employed.

#### IV. PRODUCTION OF $\Theta^+$

The  $\Theta^+$  production from the non-strange initial hadrons is furnished by the creation of  $s\bar{s}$  pair, which requires energy deposit around 1 GeV. In general the reaction mechanism of such energy region is considered to be complicated. However, as one of calculable methods, we adopt an effective lagrangian approach. Input parameters in the lagrangians should reflect the properties of  $\Theta^+$  and therefore, the comparison of calculations and experiments will help study the structure of  $\Theta^+$ . One of the most important ones is, as discussed in the previous section, the parity. Here we briefly discuss (1) photoproduction as originally performed in LEPS group [13, 14] and (2)  $\Theta^+\Sigma^+$  production induced by the polarized  $\bar{p}\bar{p}$ .

##### A. Photoproduction

As described in detail in Ref. [13], in the effective lagrangian method we calculate the Born (tree) diagrams as depicted in Fig. 3. The actual form of the interaction lagrangian depends on the scheme of introduction, i.e., either pseudoscalar (PS) or pseudovector (PV) schemes. In the PS, the three Born diagrams (a)-(c) are computed with gauge symmetry maintained. In the PV, on the contrary, the contact Kroll-Ruderman term (d) is also necessary. In the PS scheme, the contact term may be included in the antinucleon contribution of the nucleon pole terms. If chiral symmetry is respected, the low energy theorems guarantee that the two schemes should provide the same answer. In reality, due to the large energy deposit of order 1 GeV, one worries that the equivalence may be violated. It is shown that the difference in the two schemes is proportional to the kaon momentum in the first power (which therefore vanishes in the low

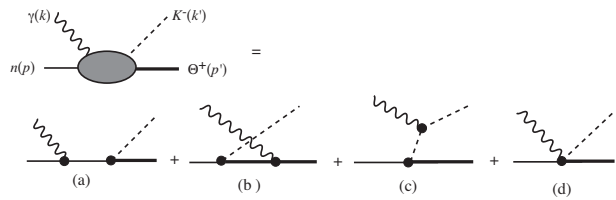


FIG. 3: Born diagrams for the  $\Theta^+$  photoproduction.

energy limit) and to the anomalous magnetic moment of  $\Theta^+$ .

In practice, we need to consider the form factor due to the finite size of the nucleon. Here we adopt a gauge invariant form factor with a four momentum cutoff [15]. This form factor suppresses the nucleon pole contributions in the PS scheme (and hence the contact term also in the PV scheme), as reflecting the fact that the nucleon intermediate state is far off-shell. Consequently, the dominant contribution is given by the t-channel process of the kaon exchange and/or  $K^*$  meson exchange. The ambiguity of the anomalous magnetic moment of  $\Theta^+$  is also not relevant. Therefore the difference between the PS and PV schemes is significantly suppressed when kaon exchange term is present as for the case of the neutron target. This allows one to make rather unambiguous theoretical predictions.

We have computed the photoproduction of  $\Theta^+$  for the neutron and proton target, and for the two parities of  $\Theta^+$ . Here are several results: (1) When the decay width  $\Gamma_{\Theta^+ \rightarrow KN} = 15$  MeV is used the typical total cross section values are about 100 [nb] for the positive parity and about 10 [nb] for the negative parity. Since these values are proportional to  $\Gamma_{\Theta^+ \rightarrow KN}$ , experimental information on the decay width is useful to determine the size of cross sections. In general the cross sections are about ten times larger for the positive parity  $\Theta^+$  than for the negative parity. The p-wave coupling  $\vec{\sigma} \cdot \vec{q}$  effectively enhances the coupling strength by factor 3–4 as compared with the s-wave coupling for the negative parity, when the momentum transfer amounts to 1 GeV. (2) For the neutron target, the kaon exchange term is dominant. In this case, the  $K^*$  contributions are not important even with a large  $K^*N\Theta$  coupling  $|g_{K^*N\Theta}| = \sqrt{3}|g_{KN\Theta}|$  [16]. Hence the theoretical prediction for the neutron target is relatively stable. The angular dependence has a peak at  $\theta \sim 60$  degrees in the center-of-mass system, a consequence of the vertex structure of the  $\gamma KK$  vertex in the kaon exchange term. Since this feature is common to both parities, the difference in the parity of  $\Theta^+$  may not be observed in the angular distribution. (3) The kaon exchange term vanishes for the case of the proton target. Therefore, the amplitude is a coherent sum of various Born terms, where the role of the  $K^*$  exchange is also important. The theoretical prediction for the proton target is therefore rather difficult.

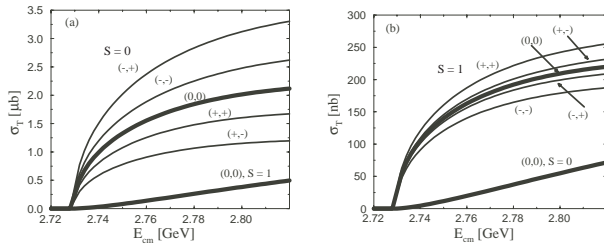


FIG. 4: Total cross sections for  $pp \rightarrow \Theta^+\Sigma^+$ , (a) for the positive parity and (b) for the negative parity, as functions of center of mass energy. Different curves correspond to different unknown coupling  $K^*N\Theta$  [13].

### B. Polarized proton beam and target

This reaction was considered in order to determine the parity of  $\Theta^+$  unambiguously, independent of reaction mechanism [17, 18]. In the photoproduction case, the determination of parity is also possible if we are able to control the polarization of both the initial and the final states [20], which is however very difficult in the present experimental setup.

The system of two protons provides a selection rule due to Fermi statistics. Since the isospin is  $I = 1$ , the spin and angular momentum of the initial state must be either  $(S, L) = (0, \text{even})$  or  $(S, L) = (1, \text{odd})$ . Now consider the reaction

$$\vec{p} + \vec{p} \rightarrow \Theta^+ + \Sigma^+. \quad (3)$$

at the threshold region, where the relative motion in the final state is in s-wave. If the initial spin state has  $S = 0$ , then the parity of the final state is positive and hence the parity of  $\Theta^+$  MUST BE positive. Likewise, if  $S = 1$  the parity of  $\Theta^+$  MUST BE negative.

One can compute production cross sections by employing an effective lagrangian of the kaon and  $K^*$  exchange model. The results are shown in Fig. 4 for both positive and negative parity  $\Theta^+$ , where the Nijmegen potential for  $K$ ,  $K^*$  exchanges [19] and decay width 15 MeV are employed. The above selection rule is shown clearly by the energy dependence at the threshold region.

Recently COSY-TOF reported the result for the  $\Theta^+\Sigma^+$  production in the unpolarized  $pp$  scattering at  $p_p = 2.95$  GeV/c [21]. They quote the total cross section  $\sigma \sim 0.4 \pm 0.2$  [ $\mu\text{b}$ ] at 30 MeV above the threshold in the center of mass energy. In comparison with theory, if we adopt a narrower width of about 5 MeV, the cross section will be about 0.5 [ $\mu\text{b}$ ] for the positive parity and 0.05 [ $\mu\text{b}$ ] for the negative parity. This comparison seems to favor the positive parity  $\Theta^+$ . Although there remain some ambiguities in theoretical calculations, such a comparison of the total cross section will be useful to distinguish the parity of  $\Theta^+$ .

### Acknowledgements

The author would like to thank K. Hicks, T. Hyodo, H.C. Kim, T. Nakano, S.I. Nam, M. Oka, E. Oset, H. Toki and A.W. Thomas for fruitful discussions.

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